Development of a Rotating Turbine Rig at Penn State to Study Secondary Flow Leakages and Aerothermal Cooling

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Outline

Research Objectives

Building Renovation and Facility Layout

Description of Proposed Rig

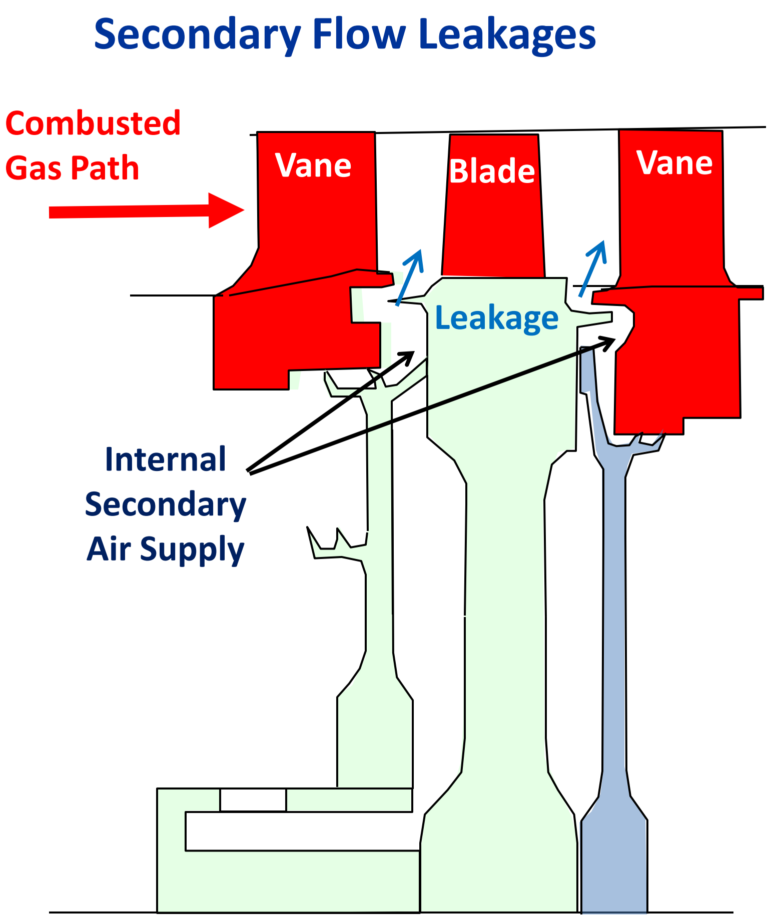
Operating Conditions

Major System Components

Aircraft Engines

Power Generation

Internal Air System (IAS) leakages lead to significant losses in gas turbines



Leakage of high pressure coolant from the internal air systems in a gas turbine equates to efficiency penalties.

These leakages, along with cooling methods for turbine components, are highly effected by rotational effects.

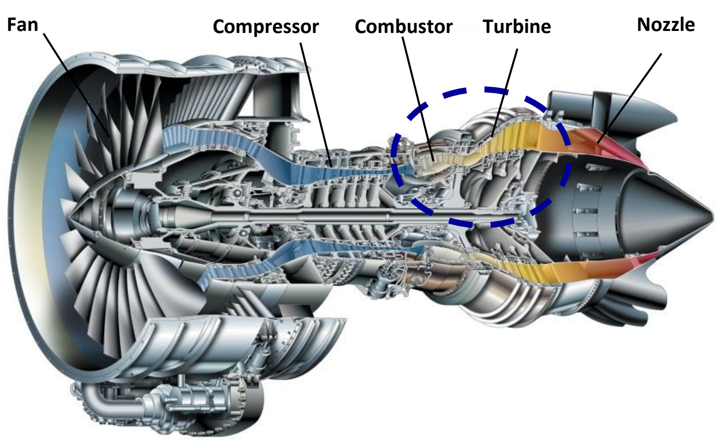
No such test facility exists in which these important effects can be simulated for matched engine conditions.

Reductions in gas turbine leakage air (TLA) from the internal air system lead to environmental and economic benefits

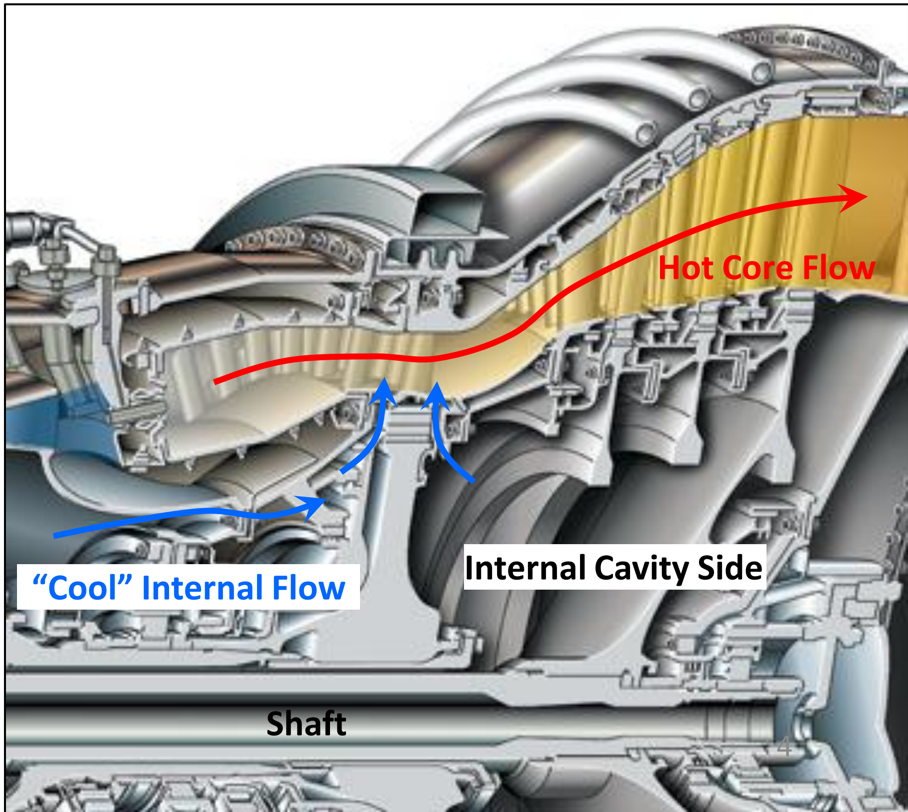
- **Potential 5% reduction in**
  - Petroleum and natural gas consumption in power-generating gas turbines
  - Jet fuel consumption of 1.4 Million barrels per day (~40% of foreign imports)

- **Reduction in Green House Gas Emissions by about 10 million metric tons per year in the US**

PW6000 Commercial Engine



[www.pw.utc.com/products/commercial/pw6000.asp]

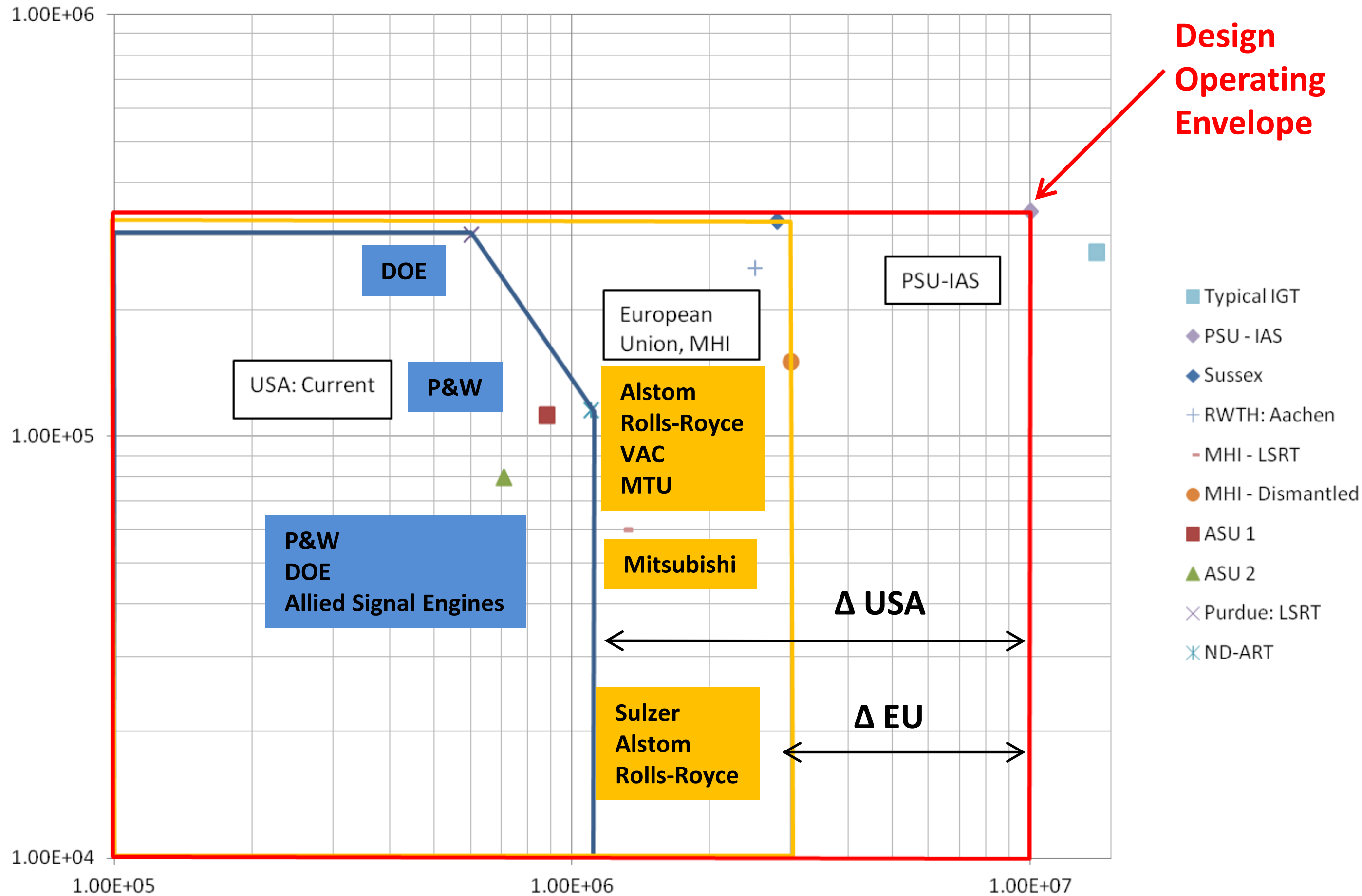


The design operating envelope for the new facility is well above most rotating turbine rigs in the U.S. and Europe

- Internal Air Systems Continuous Duration Rigs -
Parameter Space Comparison

Blade Inlet Reynolds Number

$$Re_x = \frac{\rho_{gaspath} \cdot C_x \cdot L_{chord(x)}}{\mu_{gaspath}}$$



Rotational Reynolds Number $$Re_\phi = \left.\frac{\rho \cdot \Omega \cdot R^2}{\mu}\right|_{HUB,PURGE}$$

The first research objective is to study the influence of IAS leakage flows on turbine stage aero and heat transfer

Test Campaign 1

1st vane, full stage, and 1 ½ stage
Baseline performance maps
No purge flow
CFD pre-processing

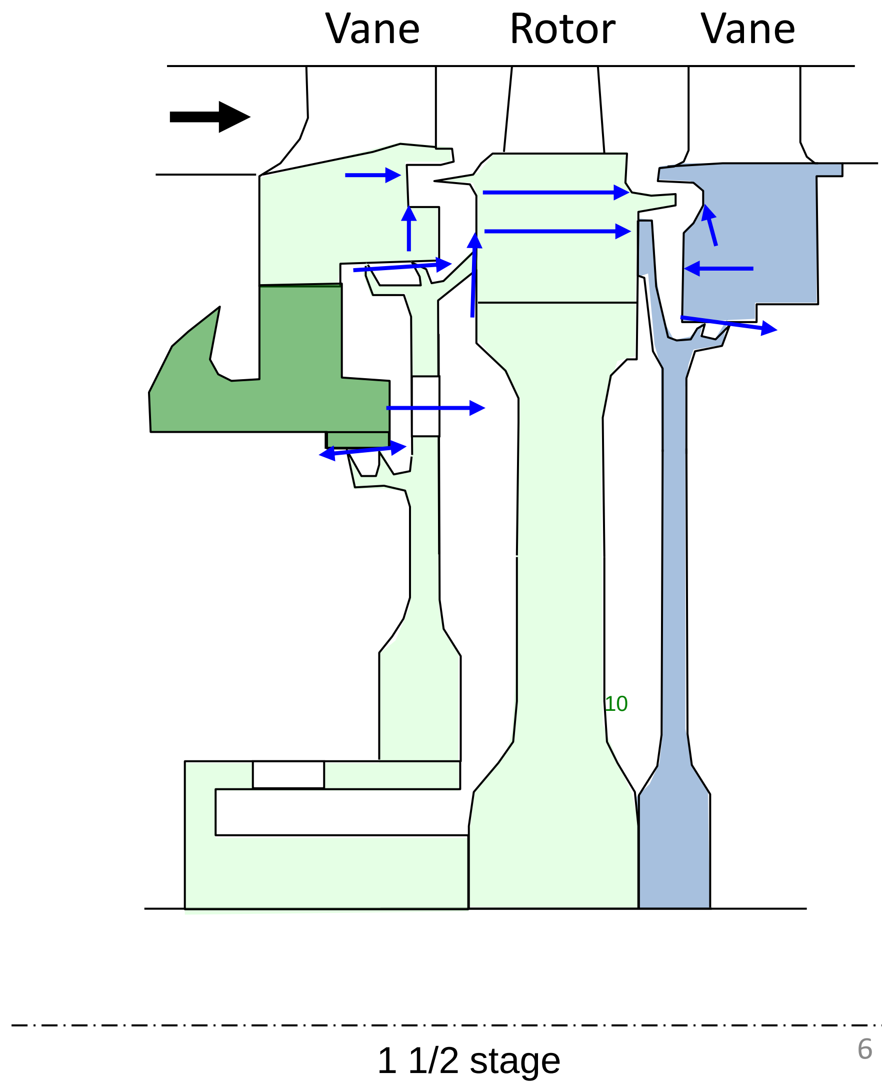
Test Campaign 2

Test purge flow egress and rotor disk cooling
Version 1
CFD work alignment

Test Campaign 3

Test purge flow egress and rotor disk cooling
Version 2 – improved design
CFD work alignment

Short Span Airfoils



The second research objective is to study cooling flow performance in airfoils under rotation and with IAS leakage

Test Campaign 4

1st vane, full stage, and 1 ½ stage
Baseline performance maps
Internal cooling flow, no purge flow
CFD pre-processing

Test Campaign 5

Internal cooling flow and purge Flow

Version 1

CFD work alignment

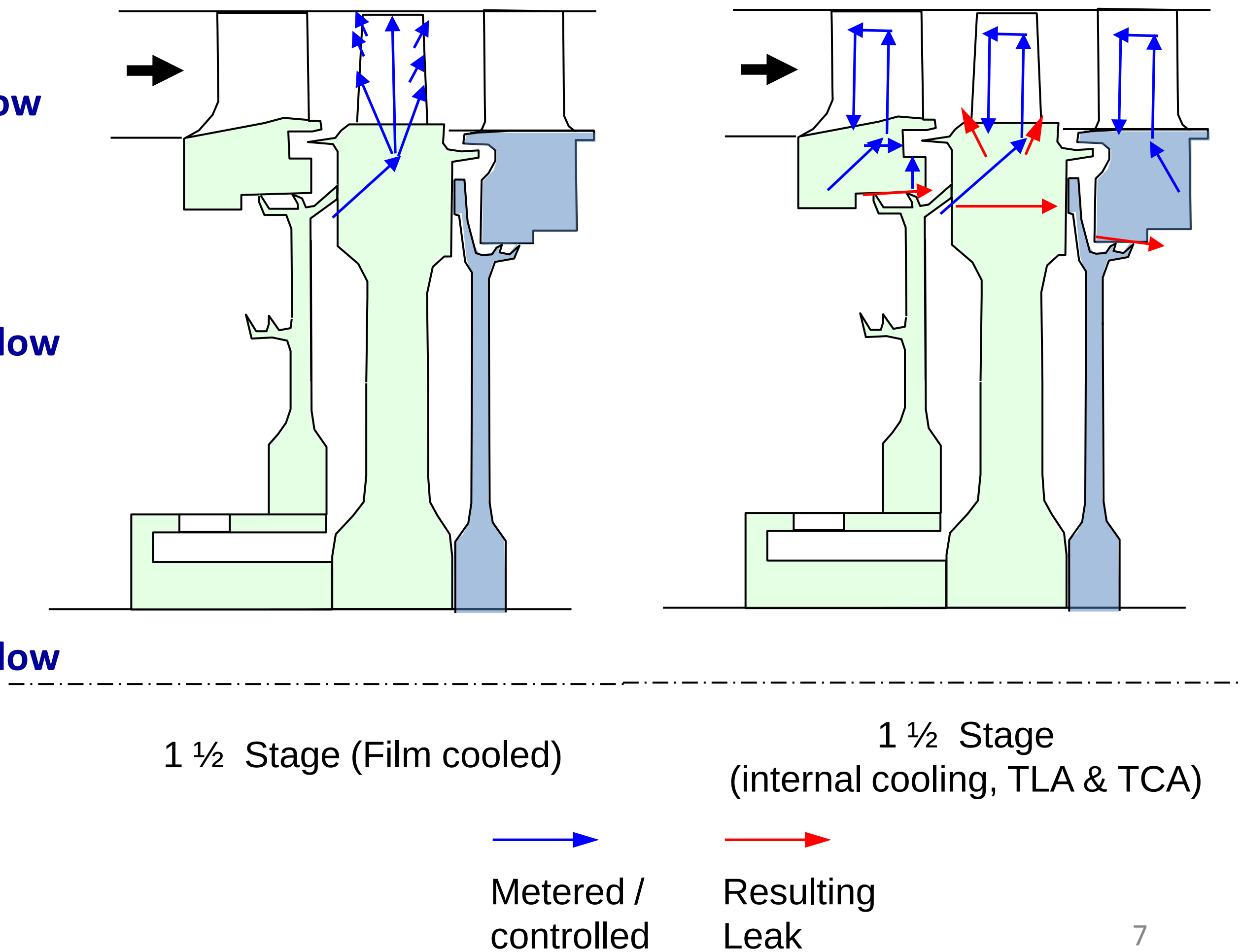
Test Campaign 6

Internal cooling flow and purge Flow

Version 2 – improved design

CFD work alignment

Full Span Airfoils



The results of the individual isolated test campaigns (1-6) will then be investigated from a full system approach

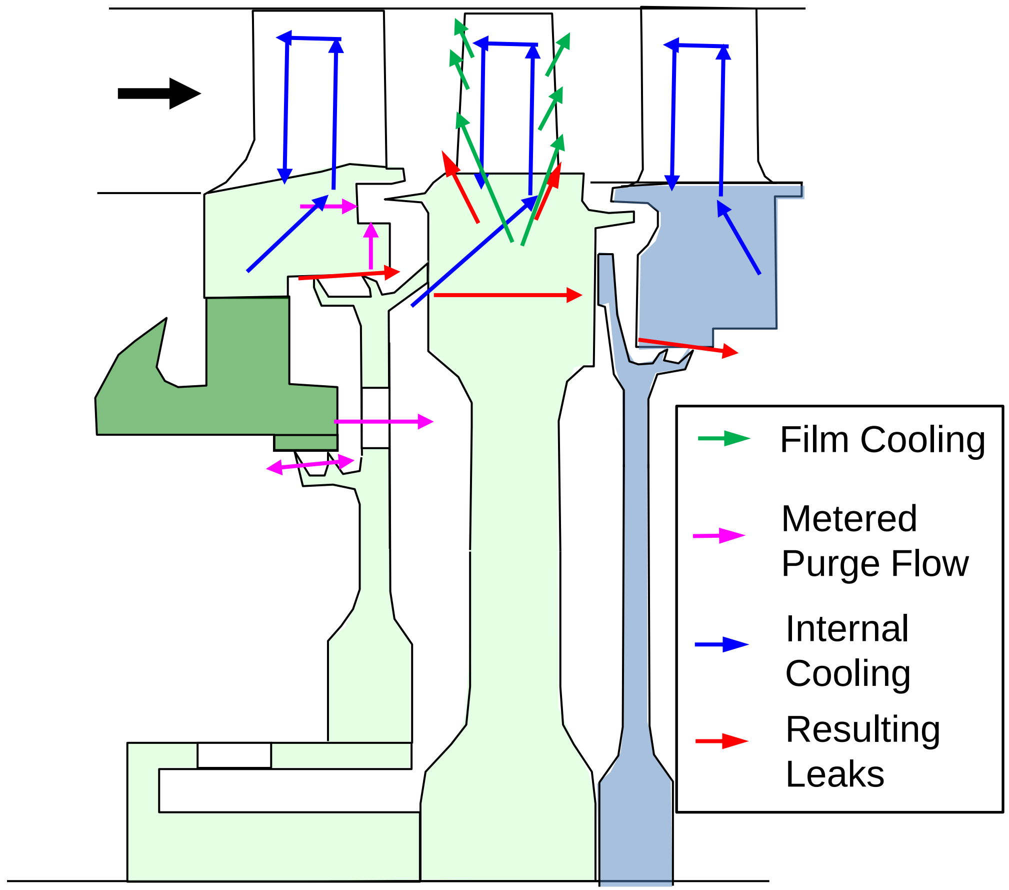
Testing of rim seals and internal cooling flows in a rotating environment

Combine Campaign 2 and 5

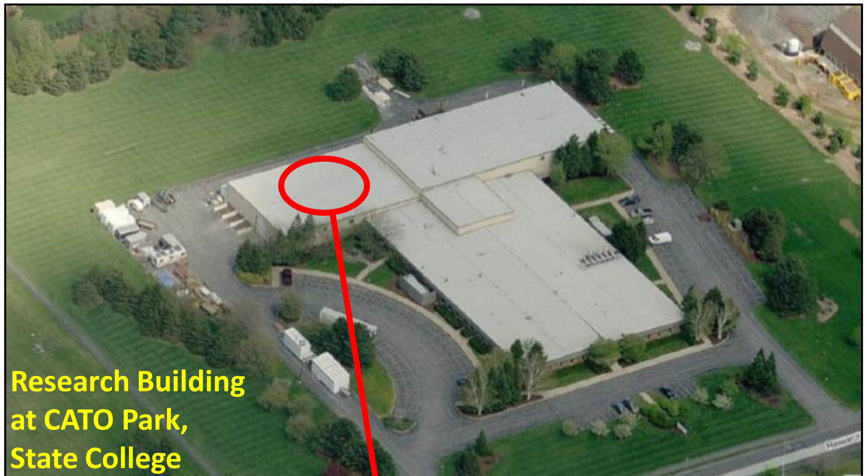
Validate combined turbine aero, blade cooling, and air system design approach on first design

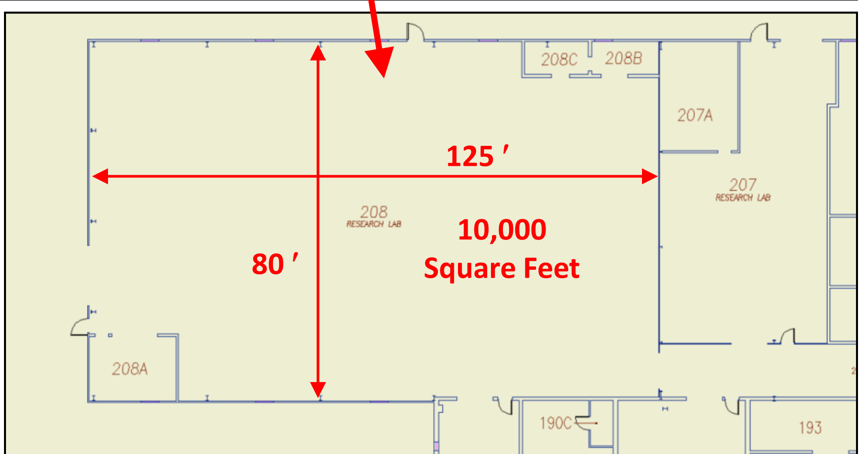
Combine Campaign 3 and 6

Validate combined turbine aero, blade cooling, and air system design approach on second, improved design



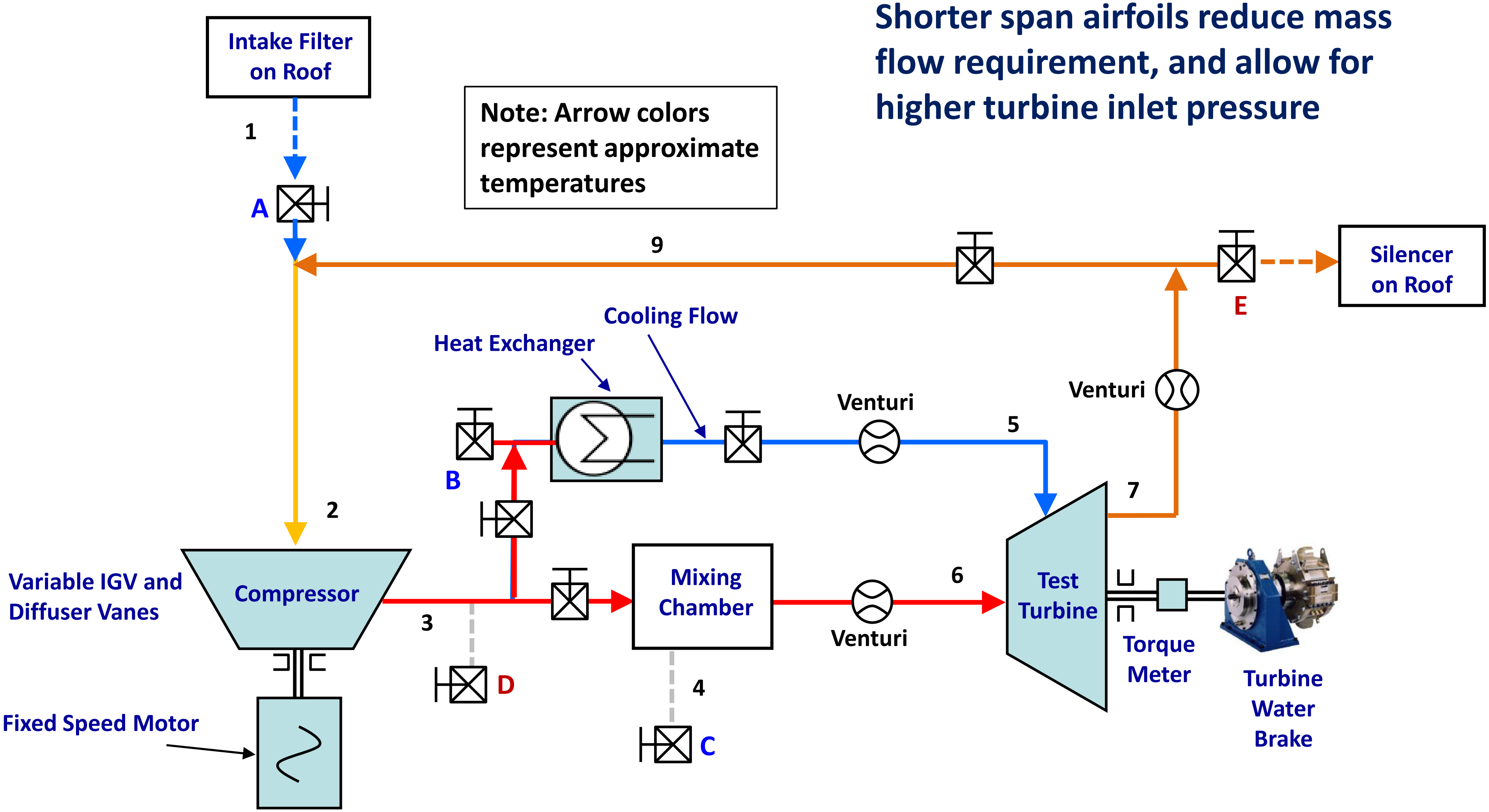
The new rotating turbine facility will be located within an existing Penn State research building in State College, PA



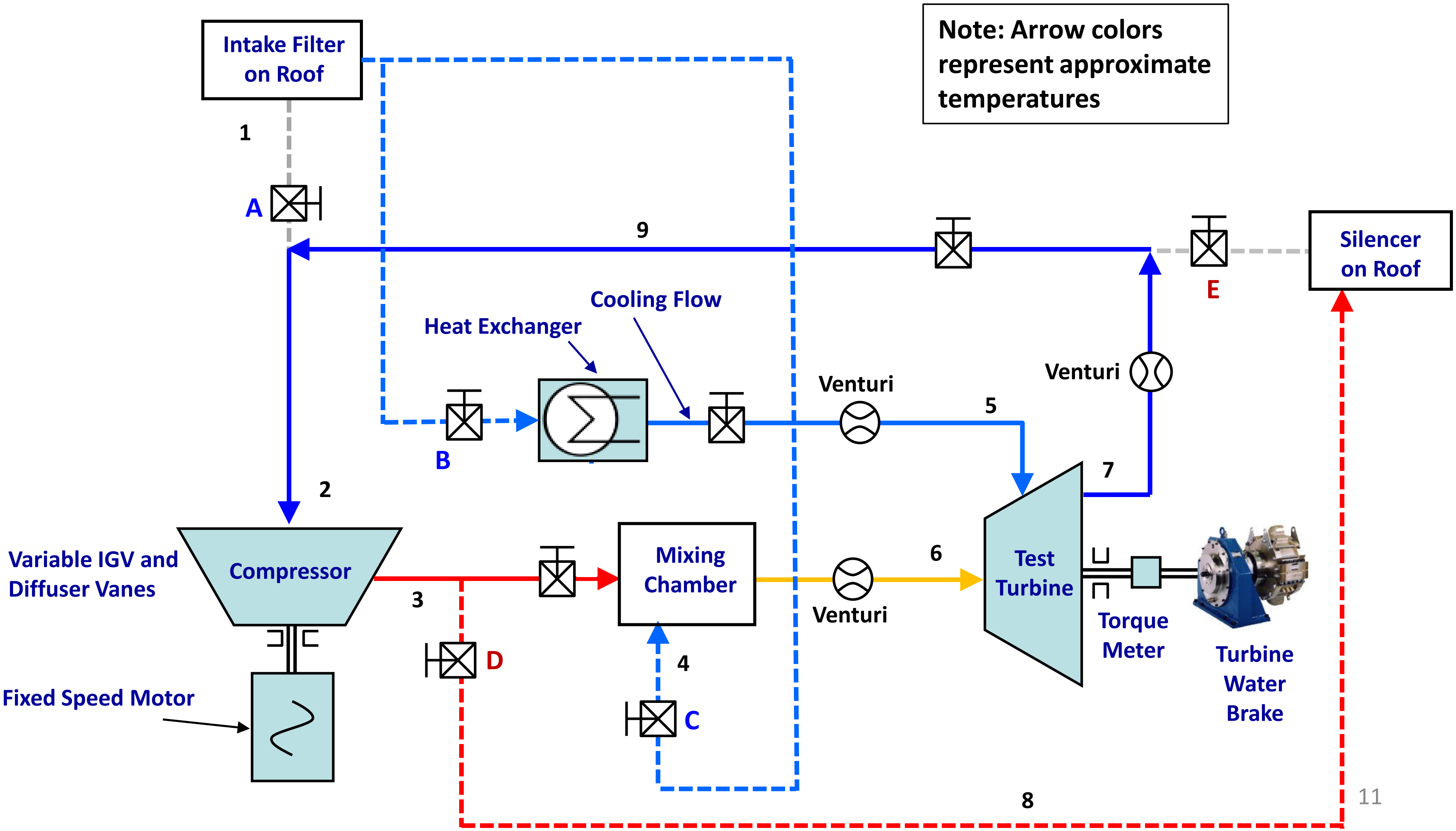


The short span turbine airfoils will be tested using a high pressure inlet condition (Campaigns 1-3)

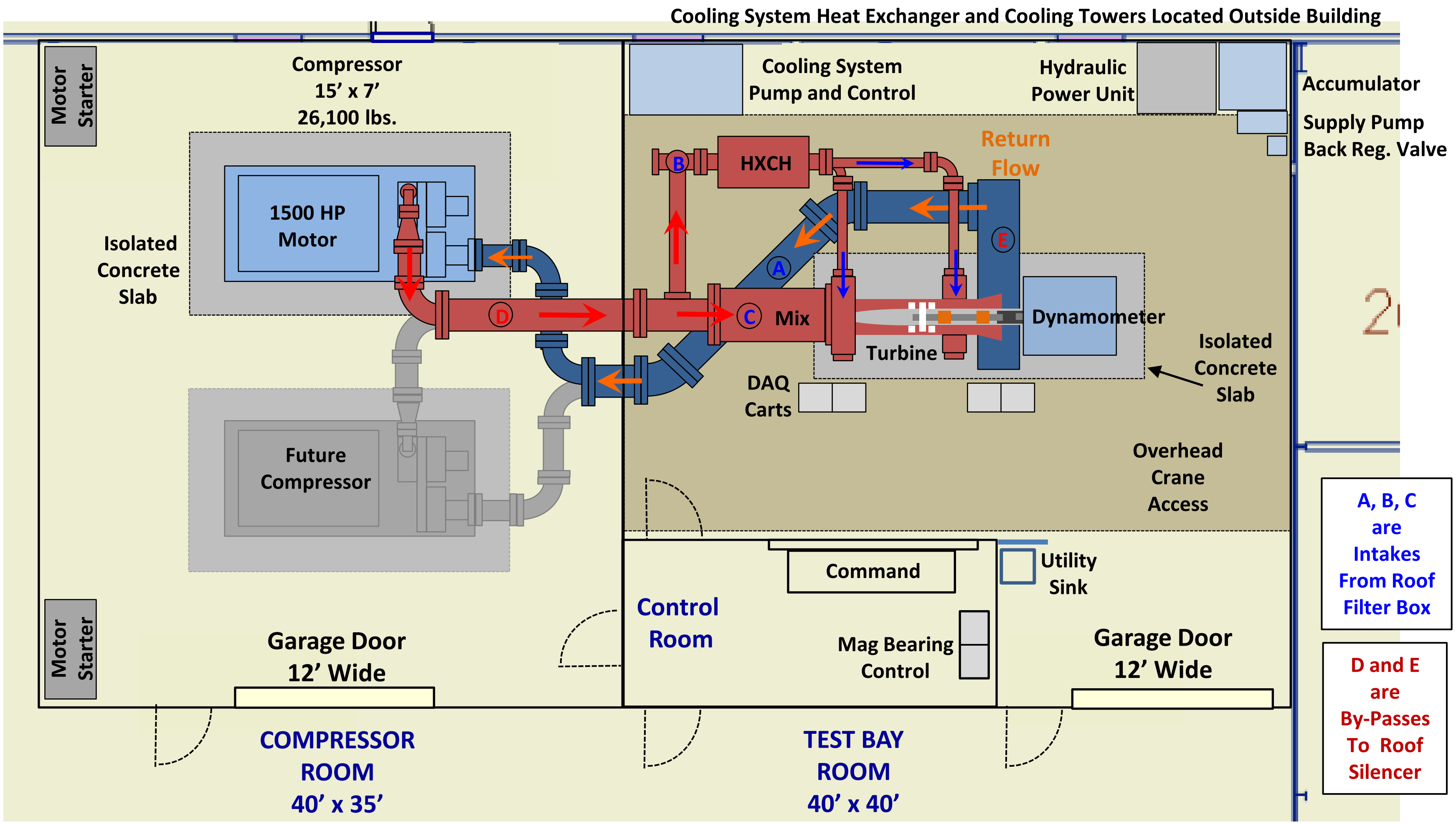
Shorter span airfoils reduce mass flow requirement, and allow for higher turbine inlet pressure



The long span airfoils will be tested using a lower pressure inlet condition (Campaigns 4-6)



The major components of the new facility were arranged within the new facility footprint at true scale



* Dark Blue Ductwork = Turbine Exhaust Flow Directed to Compressor
* Red Ductwork = Compressor Discharge Flow Directed to Turbine

Heat to Room Per Compressor
Conservative Estimate:
77.7 kW - 6.9% of 1500 HP

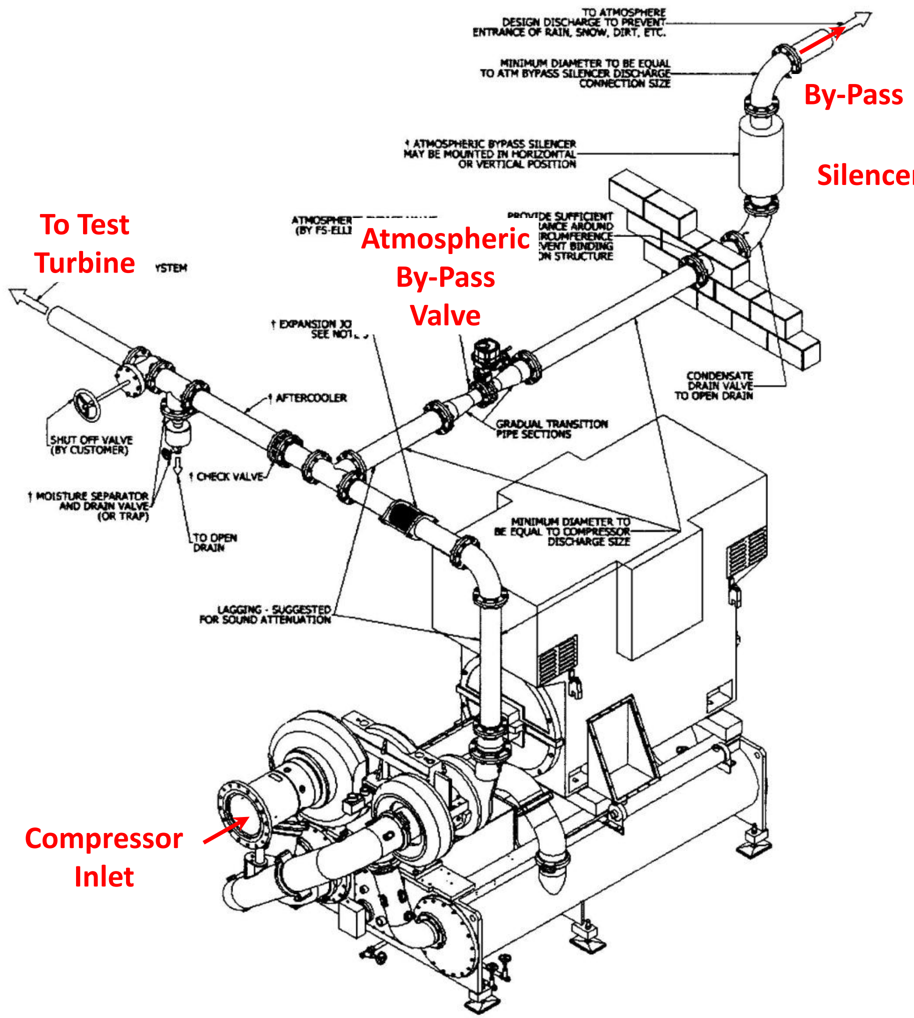
The infrastructure and safety features also drive the design of the rotating rig test facility

Facility Infrastructure

- HVAC: control room, test bay, compressor room
- Electrical: 4160V room
- Plumbing: hot/cold domestic, re-circulation for cooling
- Overhead Crane: freestanding bridge, 3-5 ton
- Concrete Slabs: isolated, reinforced
- Garage Doors: test bay, compressor room
- Lighting: work, test, hazard
- Compressed Air: pneumatic tools, shop equipment
- Noise Reduction: silencers on intake and exhaust lines
- Telecommunications: phones, internet, intranet

Safety

- Turbine Rotation: high cycle, blade containment
- Electrical: hazard areas
- Overhead Crane
- Spill Containment: floor wells/drains
- Fire Suppression: dry system
- Lighting: motion
- Storage: chemical, gas cylinder, hardware, tools
- Video Surveillance: control room monitoring of test bay
- Security System: exterior and interior locks, safe

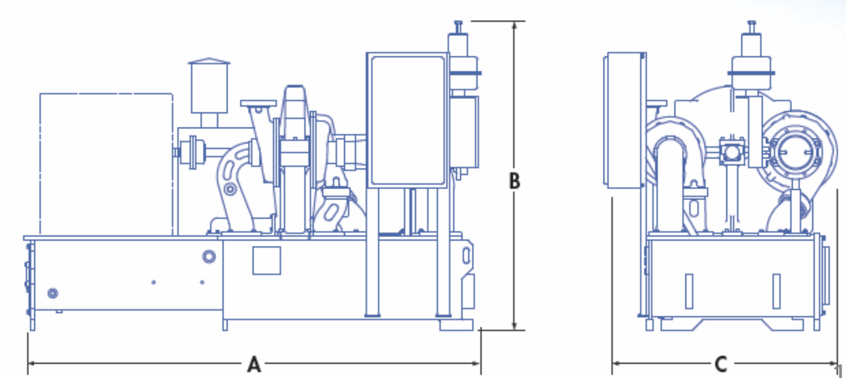


A 1500hp two stage compressor was sized to meet the research goals - producing 60 psia and 250°F at the turbine inlet with rotational speeds between 7000-11000 RPM

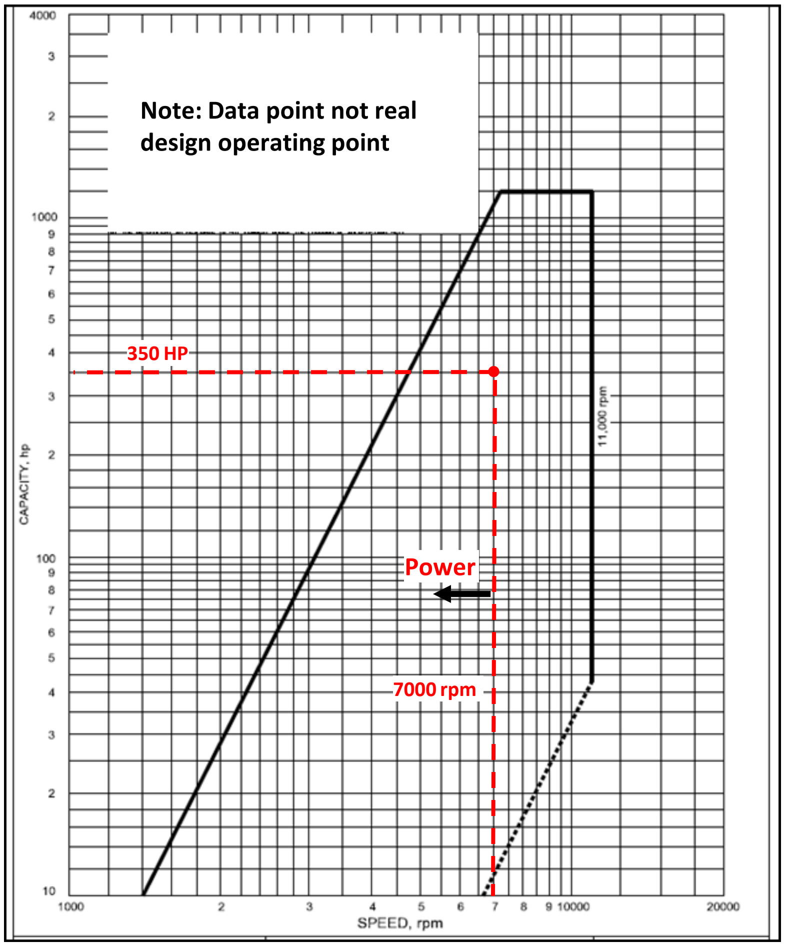
Barometric Pressure	100.0 kPa	14.5 psia
Pressure Ratio	4.2	
Inlet Pressure	98.6 kPa	14.3 psia
Inlet Temperature	308 K	70-95°F
Discharge Pressure	413.7 kPa	60.0 psia
Discharge Temperature	420 K	250-300°F
Mass Flow Rate	5.7 kg/s	12.5 lbm/s
Volume Flow Rate	11,000 SCFM	
Power Requirement	1120 kW	1500 hp

Polaris® Model	Overall Dimensions						Approximate Weight*	
	A*		B*		C*			
	in.	mm	in.	mm	in.	mm	lb.	kg
P-300	115	2910	101	2568	72	1832	10000	4550
P-400	143	3632	75	1905	81	2057	14500	6575
P-500	125	3175	85	2160	85	2160	16000	7260
P-600	181	4597	92	2337	87	2210	25500	11567
P-700	181	4597	92	2337	87	2210	28800	13063

* Value may vary with motor rating and type



The power absorption curves for several dynamometers were obtained, and the design points of the turbine were verified to be within the operating envelopes



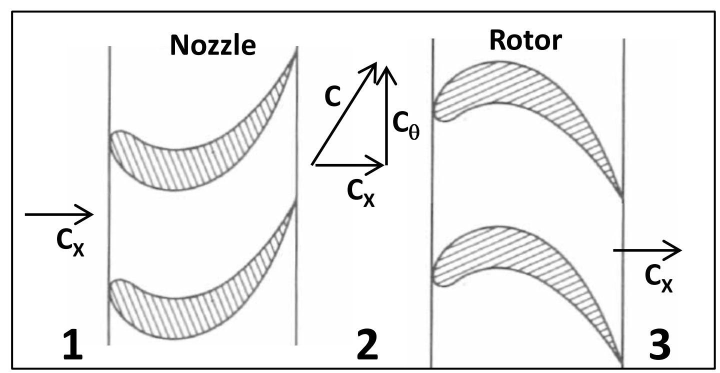
The power and torque for the test turbines were estimated using governing equations for total-to-total efficiency and anticipated pressure ratio:

$$\eta_{TT} = \frac{\dot{W}_T}{\dot{W}_{T,ideal}} = \frac{T_{01} - T_{03}}{T_{01} - T_{03s}} = \frac{1 - \left(T_{03}/T_{01}\right)}{1 - \left(P_{03}/P_{01}\right)^{\frac{\gamma-1}{\gamma}}}$$

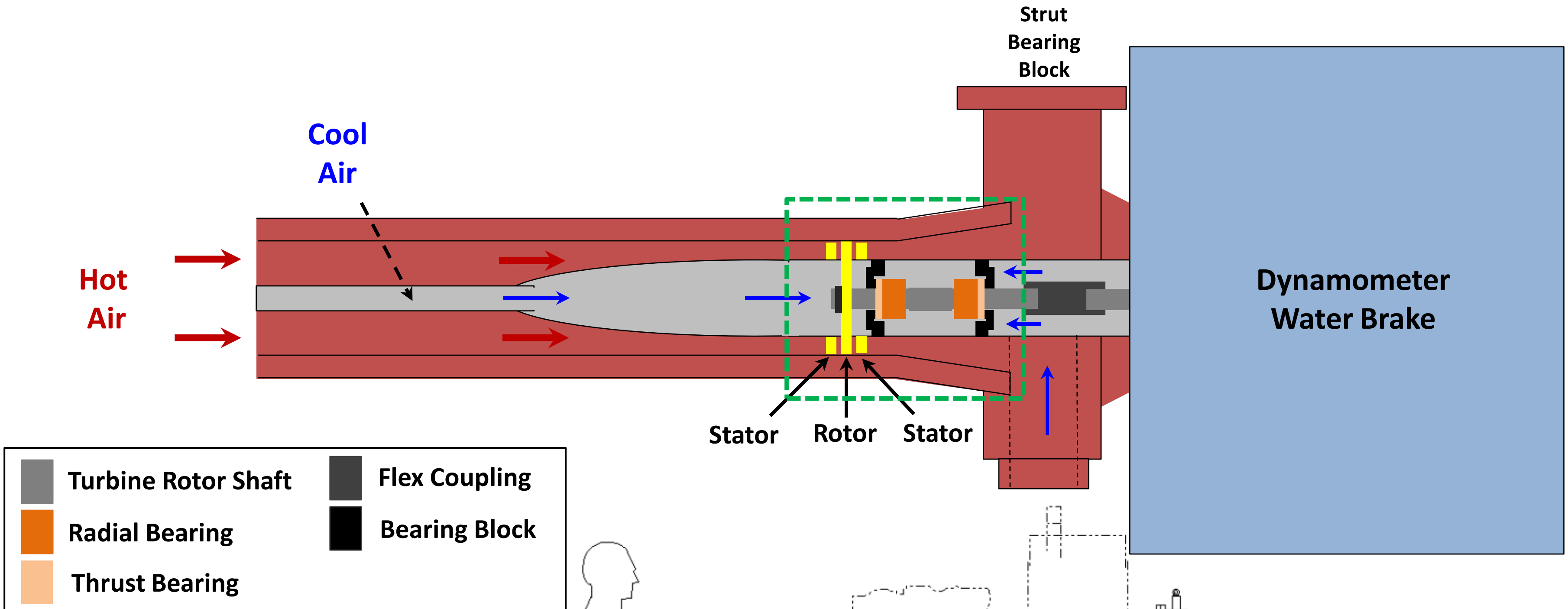
$$\dot{W}_{T,ideal} = \dot{m} \cdot C_p \cdot \left(T_{01} - T_{03s}\right)$$

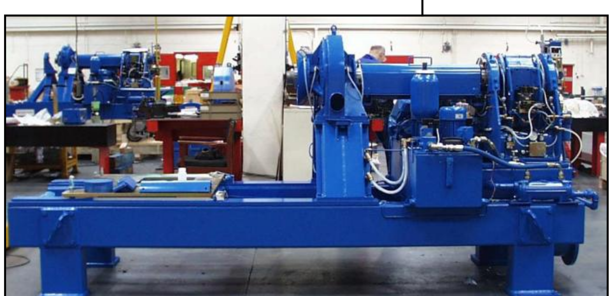
$$\dot{W} = \tau \cdot \Omega$$

$$\tau = \dot{m} \cdot \left(r \cdot C_{\theta_2} - r \cdot C_{\theta_3}\right)$$

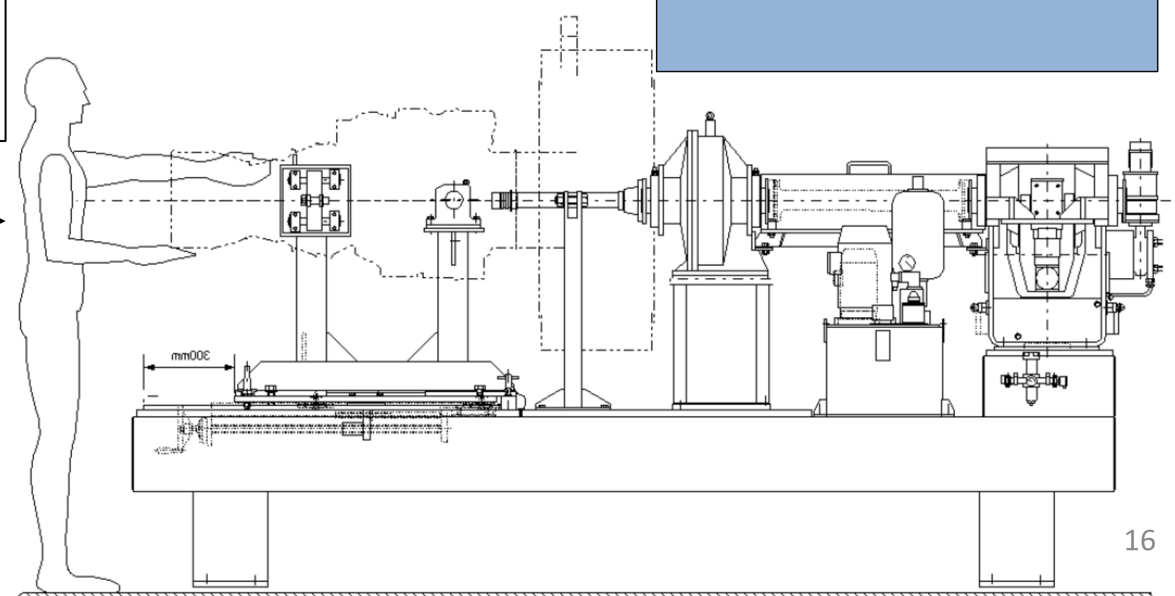


An active magnetic bearing system (radial and thrust) will be used to support and position the rotating shaft of the test turbine





Example Test Stand: Froude-Hofmann

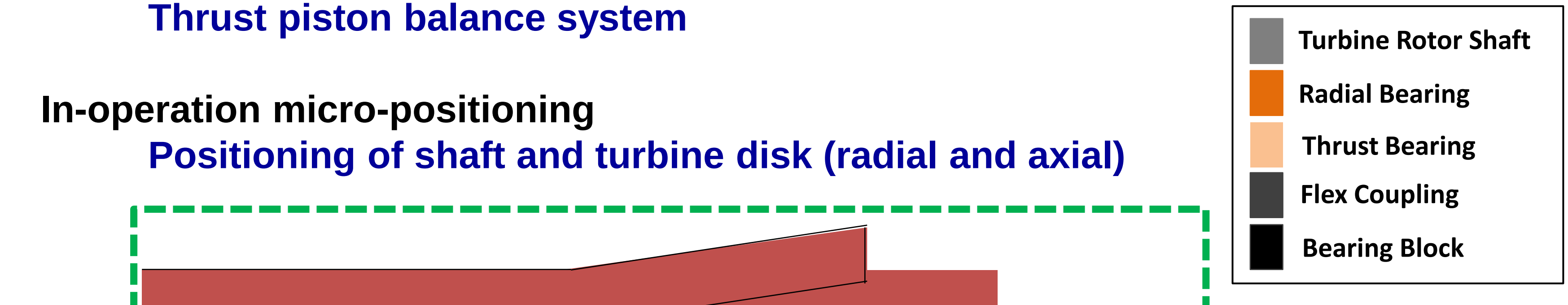


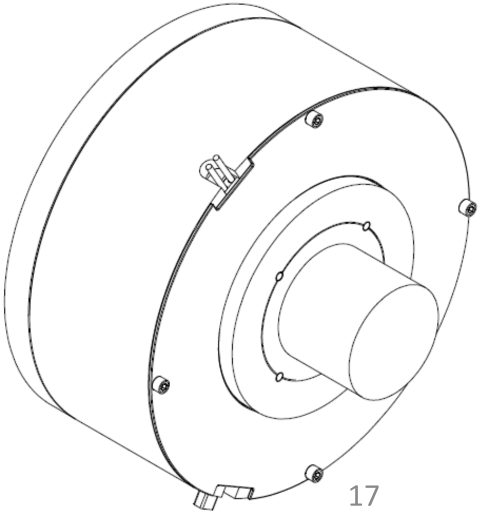
The active magnetic bearing system will support the shaft, reduce wear, and allow for shaft micro-positioning

Integrated axial and radial mag bearings
- Axial bearings – counter axial thrust on turbine
- Radial bearings – support shaft
- Auxiliary – when magnetic bearings are off

High thrust situations
- Thrust piston balance system

In-operation micro-positioning
- Positioning of shaft and turbine disk (radial and axial)





An instrumentation plan is being developed to benchmark the facility and evaluate operating conditions of the test turbine

Facility

- Ductwork flow pressures and temperatures, venturi flow meters

Turbine Test Section

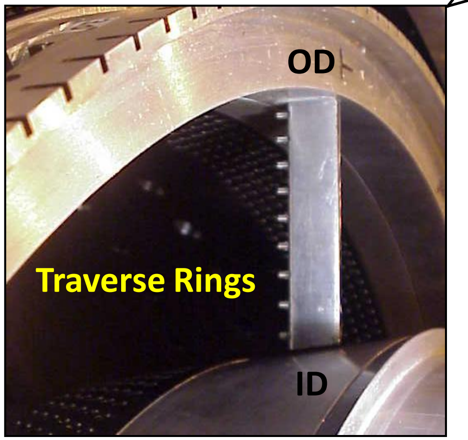
- Core flow pressure, temperature, turbulence
- Airfoil and endwall platform pressures and temperatures
- Cavity and seal pressures and temperatures
- Turbine disk pressure and temperatures
- Telemetry system

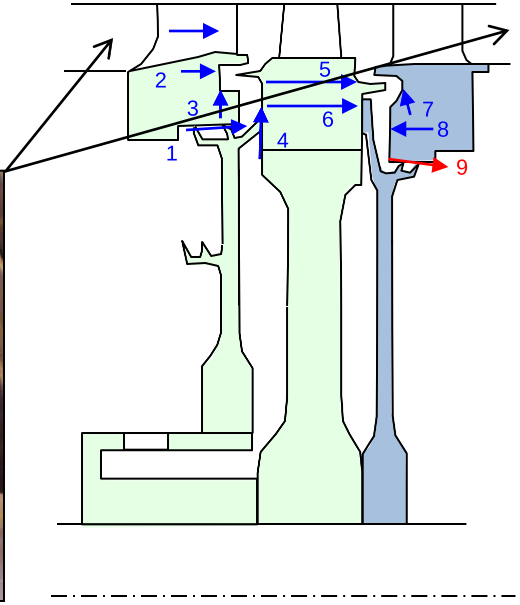
Probes

- Thermocouples, RTD's
- Kiel and Static
- Gas composition
- Proximity/Non-contact Displacement

DAQ and Power

- High speed and low speed
- DC power supplies





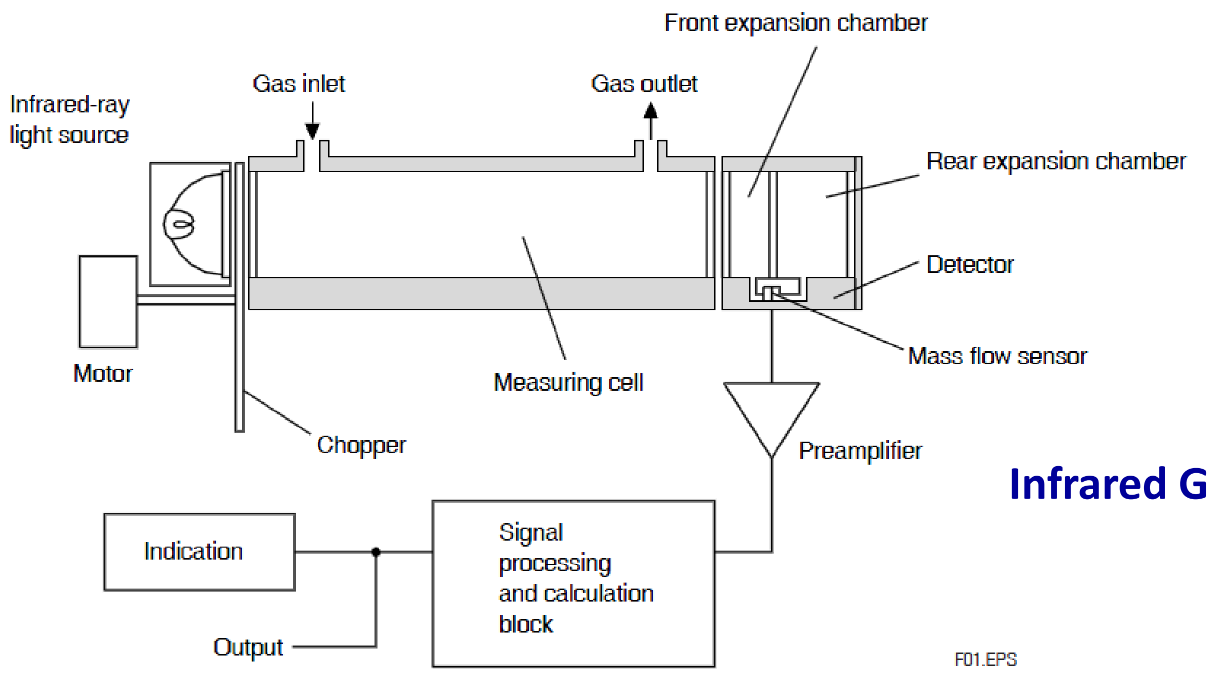
Various methods have been used to take measurements in existing rotating turbine test rigs

Purge mass flow rate
- Mass flow meter (Notre Dame, US)
- Orifice plates (University of Bath, UK)

CO_2 concentration
- Infrared gas analyzer (Bath; Sussex)
- Taps directed to gas analyzer (UTRC, Bath)

Upstream/Downstream traverse rakes
- Kiel pressure probes and total temperature probes
- Piecewise casing construction (ND)

Turbulence Intensity
- Hot-wire anemometry (ND)



Infrared Gas Analyzer[1]

[1] *[Yokogawa Electric Corporation: diagram for IR200 Universal Infrared Gas Analyzer]*

Various methods have been used to take measurements in existing rotating turbine test rigs

Cavity pressures and temperatures

- **Kulite pressure transducers (Ohio State, US)**
- **Miniature butt-welded thermocouples (OSU)**
- **Pressure taps (Sussex)**

Disk pressures and temperatures

- **Kulite pressure transducers**
- **Thermocouples**

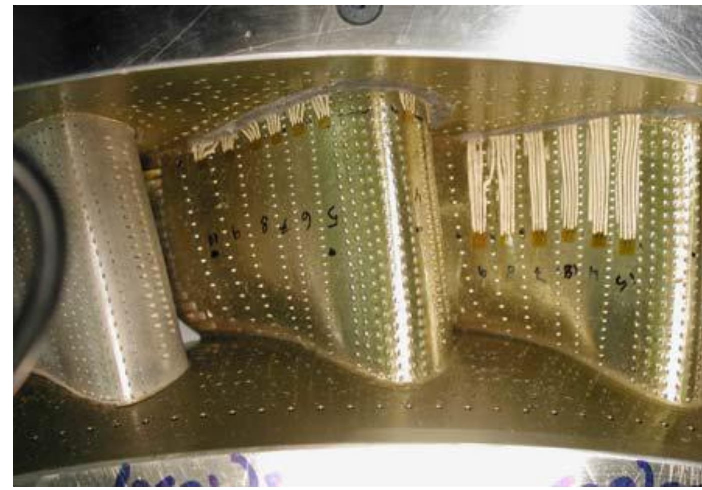
Airfoil endwall pressures/temperatures

- **Flush-mounted pyrex heat-flux gauge: temperature and heat-flux (OSU)**
- **Partially-protruding thermocouples on endwall (OSU)**

Data transmission

- **Slip ring (OSU)**
- **Telemetry system (Bath)**

Pyrex heat-flux gauge[1]
Ohio State University

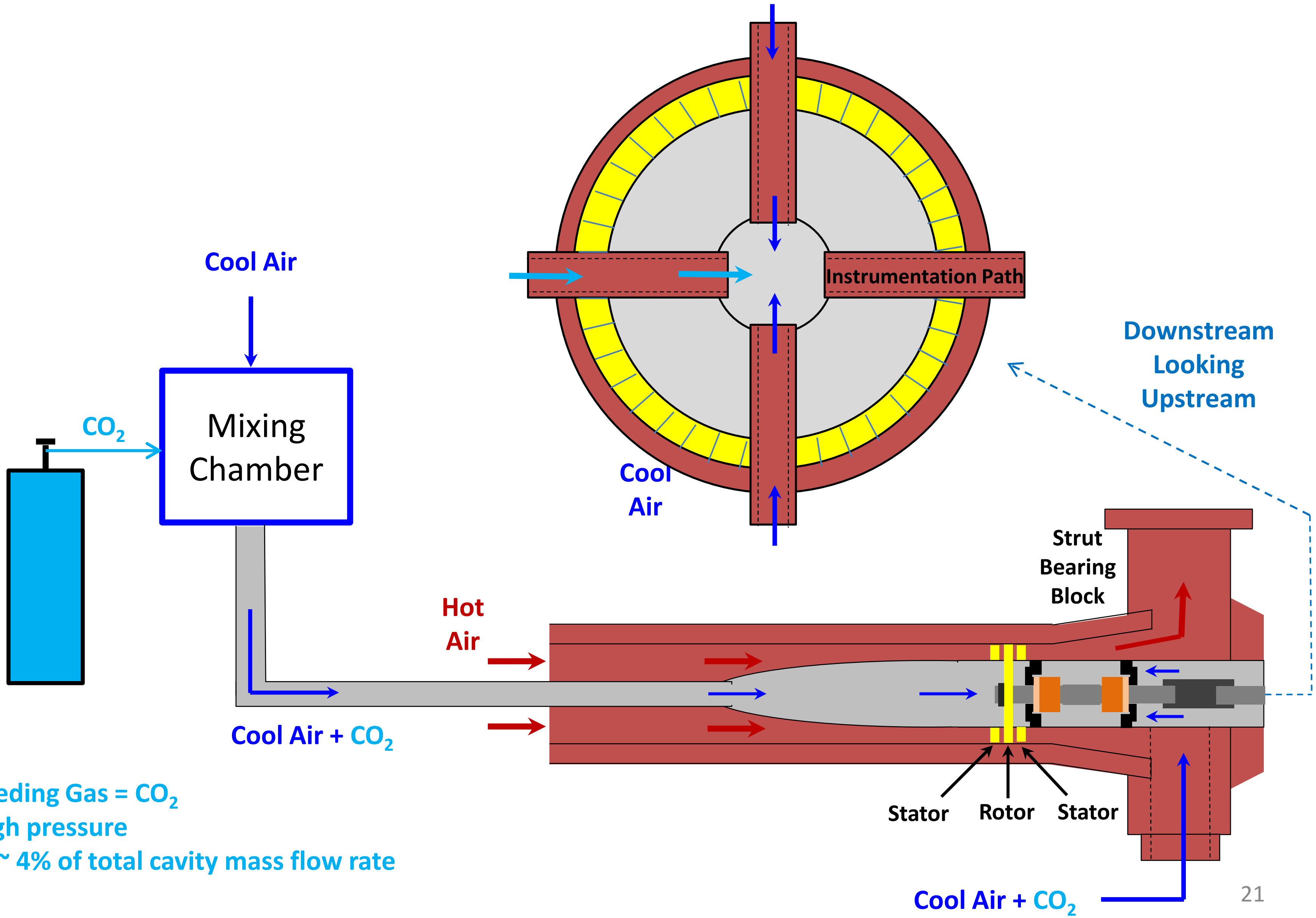


Mini-telemetry module[2]
University of Bath

Static antenna

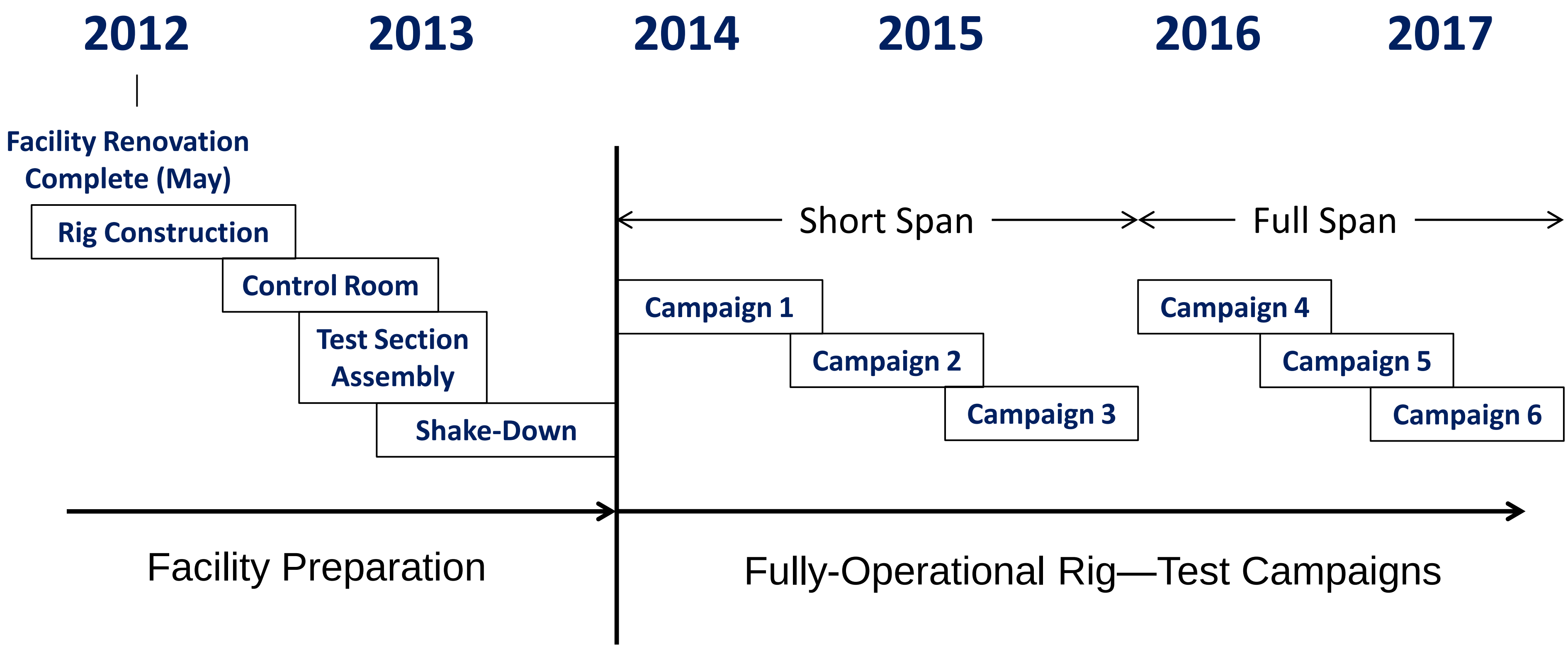
[1] *[Kahveci, H., Haldeman, C., Mathison, R., Dunn, M. 2011 (Turbo Expo GT2011-46570)]*
[2] *[Long, S., et al, 2011 (Turbo Expo GT2011-45910)]*

Carbon dioxide tanks will be used to deliver CO_2 seeding gas to the purge cavity flow



Seeding Gas = CO_2
High pressure
$\dot{m}$ ~ 4% of total cavity mass flow rate

Timeline



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The Inlet Profile Generator (IPG) at the AFRL TRF was heavily instrumented to monitor various flow streams and surface temperatures

Flow Measurements

- (14) Pitot-Static Pressure Probe
- (16) Kiel Pressure Probe
- (12) Total Temperature Probe

Surface Measurements

- (6) Miniature KULITE Transducer
- (8) Surface Embedded TC
- (8) Surface Mounted RTD